Watching Earth from Space

How Surveillance Helps Us – And Harms Us

Pat Norris

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Author's preface

Surveillance cameras are difficult to avoid, from the CCTV cameras in streets, lobbies and shops to the cameras at traffic signals and roadside speed traps. There are cameras in outer space watching us too – not as obvious as the street level variety, but there nonetheless – and their number is increasing rapidly as costs fall and more countries want one that carries their flag. Occasionally they are discussed by the media as when Vice President Cheney's home was deliberately blurred in the satellite image on Google Earth. This book catalogs the main reasons why satellites in outer space are watching the earth. Many of the reasons are benign while others are deliberately intrusive. The theme of the book is that by and large Earth-watching satellites are a good thing.

I was overwhelmed by the assistance I received from friends and colleagues, old and new, in collecting the material presented in the book. If it contains errors or ambiguities, it is because of my failure to correctly interpret their material. The long list of those who helped includes (in alphabetical order) Paul Brooks, Simon Casey, Jeremy Close, John Davey, Mark Drinkwater, Roy Gibson, Anders Hansson, Ray Harris, Dave Hodgson, David Keighley, Adam Keith, Bob Kelley, Hans Kristensen, Robert Meisner, Amy Norris, Allison Puccioni, Ray Purdy, Nick Shave, David Southwood, Sir Martin Sweeting, Nick Veck, Joanne Wheeler. Bob Kelley's contribution was particularly important as without him, chapter 7 on the monitoring of nuclear materials, would not have been possible. To them and all the others who helped me without hesitation, I extend my sincere thanks.

I have tried to attribute copyrights for the images used where they were evident. If anyone wishes to claim an image, I will happily amend the appropriate caption in the next edition of the book.

Pat Norris
August 2010

This book is dedicated to Valerie

Figures

Tables

Abbreviations and acronyms

ABAAC	Argentine–Brazilian Agency for Accounting and Control of Nuclear Materials
ACRIM	Active Cavity Radiometer Irradiance Monitor
ADEOS	ADvanced Earth Observing Satellite
AIS	Automatic Identification System
AIT	Aerial Imaging Team
ALOS	Advanced Land Observation Satellite
ARTEMIS	Advanced Relay and TEchnology MISsion
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVHRR	Advanced Very High-Resolution Radiometer
AVNIR	Advanced Visible and Near Infrared Radiometer type
BATMAV	Battlefield Air Targeting Micro Air Vehicle
BIRA-IASB	Belgisch Instituut voor Ruimte-Aëronomie – Institut d'Aéronomie Spatiale de Belgique
CAP	Common Agricultural Policy
CBERS	China–Brazil Earth Resources Satellite
CCD	Charged Couple Device
CCTV	Closed Circuit Television
CGMS	Coordination Group for Meteorological Satellites
CIA	Central Intelligence Agency
CLS	Collect Localization Satellites
CNES	Centre National d'Etudes Spatiales
CNSC	Canadian Nuclear Safety Commission
COMINT	Communications intelligence
COMS	Communication, Ocean and Meteorological Satellite
CoReH$_2$O	Cold Regions Hydrology High-resolution Observatory
CSIST	Chung-Shan Institute of Science and Technology
DC	District of Colombia
DEM	Digital Elevation Model
DMC	Disaster Monitoring Constellation
DMSP	Defense Meteorological Satellites Program

DoD	Department of Defense
DRC	Democratic Republic of the Congo
DRTS	Data Relay Test Satellite
DSP	Defense Support Program
EGNOS	European Geostationary Navigation Overlay System
ELINT	Electronic Intelligence
Elisa	ELectronic Intelligence SAtellite
ELT	Extremely Large Telescope
EMP	Electromagnetic pulse
EORSAT	ELINT Ocean Reconnaissance Satellites
ERTS	Earth Resources Technology Satellite
ESA	European Space Agency
fAPAR	fraction of Absorbed Photosynthetically Active Radiation
FBI	Federal Bureau of Investigation
GAGAN	GPS Aided Geostationary Augmented Navigation
GB	Gigabyte
GCHQ	General Communications Headquarters
GDACS	Global Disaster Alert and Coordination System
GEO	Geostationary Earth Orbit
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GRU	Glavnoye Razvedyvatel'noye Upravleniye (Soviet military intelligence agency)
GSFC	Goddard Spaceflight Center
HIRU	Hemispherical inertial reference unit
HQ	Headquarters
IAEA	International Atomic Energy Agency
ICBM	Intercontinental Ballistic Missile
IED	Improvised Explosive Device
IGS	Information Gathering Satellite
IMS	Indian Mini-Satellite
INPE	Instituto Nacional de Pesquisas Espaciais
INVO	Iraq Nuclear Verification Office
IPCC	Inter-governmental Panel on Climate Change
IRS	Indian Remote Sensing Satellite
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
JPSD	Joint Precision Strike Demonstration
JWST	James Webb Space Telescope
KARI	Korean Aerospace Research Institute
KGB	Komitet gosudarstvennoy bezopasnosti (Soviet security agency)
KH	Keyhole
LDCM	Landsat Data Continuity Mission

LEO	Low Earth Orbit
Lidar	Light detection and ranging
LIMES	Land and Sea Monitoring for Environment and Security
LUSI	Lumpur (mud) Sidoarjo
MIRV	Multiple Independently-targetable Re-entry Vehicle
MODIS	Moderate Resolution Imaging Spectroradiometer
MSAS	Multi-functional Satellite Augmentation System
MSG	Meteosat Second Generation
MTCR	Missile Technology Control Regime
MTSAT	Multi-mission Transport Satellite
MUSIS	Multinational Space-based Imaging System
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NASIC	National Air and Space Intelligence Center
NATO	North Atlantic Treaty Organisation
NCDC	National Climatic Data Center
NESDIS	National Environmental Satellite, Data, and Information Service
NGA	National Geospatial-Intelligence Agency
NGDC	National Geophysical Data Center
NGEO	Next Generation Electro-Optical
NGO	Non-Governmental Organization
NOAA	National Oceanic & Atmospheric Administration
NOSS	Naval Ocean Surveillance Satellite
NPIC	National Photographic Interpretation Center
NPOESS	National Polar Orbiting Environmental Satellite System
NPT	Nuclear Non-Proliferation Treaty
NRO	National Reconnaissance Office
NSA	National Security Agency
NSG	Nuclear Suppliers Group
OCHA	Office for the Coordination of Humanitarian Affairs
OECD	Organisation for Economic Cooperation and Development
OPCW	Organization for the Prevention of Chemical Weapons
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping
R&D	Research and Development
REDD+	Reducing Emissions from Deforestation and forest Degradation in developing countries
RORSAT	Radar Ocean Reconnaissance Satellites
SALT	Strategic Arms Limitation Treaty
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar or Search And Rescue
satnav	Satellite navigation
SBIRS	Space-Based Infra-Red System
SDS	Space Data Systems
SIAU	Satellite Imagery Analysis Unit

SSOT	Sistema Satelital para Observacicœn de la Tierra
SSTL	Surrey Satellite Technology Limited
TAS	Thales Alenia Space
TDRSS	Tracking and Data Relay Satellite System
TES	Technology Experiment Satellite
TSF	Télécoms Sans Frontières
TV	Television
UCAR	University Corporation for Atmospheric Research
UHF	Ultra High Frequency
UK	United Kingdom
UN	United Nations
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
UNMOVIC	United Nations Monitoring, Verification and Inspection Commission
UNOSAT	UN Institute for Training and Research (UNITAR) Operational Satellite Applications Programme
UNSC	UN Security Council
UNSCOM	UN Special Commission
URENCO	URanium ENrichment COmpany
USA	United States of America
USAF	US Air Force
VLT	Very Large Telescope
VoIP	Voice over Internet Protocol
VP	Vice-President
VT	Victoria Terminal (Mumbai)
WAAS	Wide Area Augmentation System
WHO	World Health Organization
WiFi	A play on the term "high fidelity" involving wireless broadband
WMD	Weapons of Mass Destruction
WMO	World Meteorological Organisation

1

The threat of satellite images

SATELLITE IMAGES HIT THE HEADLINES

“Google Earth helps extremists terrorise Mumbai,” scream the headlines as more than 170 people are killed in November 2008. The gunmen came ashore on the evening of November 26th and made their way to targets across the south of the city of 13 million.

The attackers all came from Pakistan and were unfamiliar with India’s most populous city. One of the gunmen was captured alive, and police say he confirmed that Google Earth was used to familiarize the gang with the streets of Mumbai. Mumbai lawyer Amit Karkhanis filed a petition at the Mumbai High Court calling for Google Earth images of sensitive areas to be blurred so as not to aid future terror groups.[1]

Confirmation of the perceived threat posed by satellite images comes from reports that then US Vice-President Dick Cheney persuaded Google Earth to blur images of his home in Washington, DC.

British soldiers fighting insurgents in southern Iraq are considering suing Google Earth based on evidence that the imagery was being used to target mortar attacks on the army’s base near Basra. “The terrorists know exactly where we eat, sleep and go to the toilet,” one soldier said.[2]

The addition of the Street View feature to Google Earth has incensed privacy campaigners even more. Satellite images and maps have now been joined by high-quality ground-level photos in many of the areas covered by Google Earth. Greece has banned Google from expanding the Street View service. In Japan, Google has had to reshoot its photos closer to the ground to avoid looking over fences. A formal complaint against Street View in Britain was dismissed by the UK’s Information Commissioner, although he ruled that it carried a risk of invading privacy.[3]

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[1] Blakely (2008).

[2] Harding (2007).

[3] BBC (2009).

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The Obama Administration has officially confirmed that satellite images are a threat to privacy. The Bush Administration had authorized domestic security agencies to receive spy satellite imagery previously seen only by the military and the CIA. However, Obama's Homeland Security chief, Janet Napolitano, killed that plan in response to concerns from privacy groups. Californian Democratic Congresswoman Jane Harman said the previous Administration's plan "was an ill-conceived vestige of the 'dark side' counterterrorism policies of the Bush years" and "just an invitation to huge mischief". Welcoming the decision to halt the domestic use of spy satellites, she said "it showed real leadership on the part of [Homeland Security Director] Janet Napolitano".[4]

It seems that satellites can spy on us from space and pose a threat to our safety and privacy.

But how real is this threat? Could it be media exaggeration or political spin?

Let's examine each of the stories above – Mumbai, Dick Cheney's house, the Iraq mortar threat and Janet Napolitano's action – to see how much is hype and how much is reality.

First, let's understand what satellites can and can't see from space.

WHAT CAN A SATELLITE SEE FROM SPACE?

Satellites fly across the sky unimpeded by borders, typically 200–800 km above the ground. With a camera onboard, they can take photographs of the ground below (if there are no clouds in the way). Many satellites carry cameras for benign reasons, such as weather forecasting or environmental monitoring, but some are explicitly seeking military information, and these we call spy satellites. If they have a suitable radio receiver, they can listen in to whatever radio signals are being transmitted below and this sort of satellite usually has a military objective. In this part of the story, the camera-carrying satellites are the main focus of the story but I will return to the radio listening satellites in Chapter 9.

Modern spy satellites are like a camera-equipped cell phone – with a very long telescope attached. You take a photo of an interesting scene using the built-in camera of your cell phone. The image is stored in the computer-style memory of the phone. Then, you send it to whoever is interested in it via the cell phone network – in other words, by radio link.

The number of pixels in the image taken by the phone-camera dictates its graininess or resolution, namely the ability to blow it up and see further detail. The more pixels in the camera, the more you can magnify it without it becoming grainy. On the other hand, the more pixels in an image, the fewer the images you can store in the memory and the more you pay to transmit it over the network. You can zoom in on the subject before taking the photo, in which case you will see more detail in the final image but less of the surroundings.

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[4] Sullivan (2009), and Hsu (2009).

Sometimes, there is no network coverage where you have taken the picture and you have to wait until your journey brings you to an area with network coverage before you can send it. If this is a frequent occurrence, you may consider switching to another network that offers better coverage.

This same outline could as easily apply to a modern spy satellite, leaving aside the fact that it takes its pictures at a distance of 200 km or more through a telescope. It takes images – automatically to a predetermined schedule rather than when a human touches a button. The heart of the camera is the same technology as in the digital camera or cell phone you buy in the high street – probably a charged couple device (CCD), which is a form of solid-state electronics similar to the transistor and the computer chip, which turns light into electrical messages. The images are stored in computer memory on the satellite, which can only hold a certain number of images before it reaches its capacity. The images may be radioed to ground immediately, but frequently there isn't a friendly ground station within sight of the satellite so it waits until its orbit brings it within the coverage of its ground network.

The USA and Russia have installed extra network relay stations to improve the coverage and thus get images back to ground from more or less anywhere in the world. The relay stations are actually satellites located at suitable very high orbits that relay the images from the spy satellite to the relevant ground network. These satellites therefore have no intrinsic limitation as to the number of images they take, provided the radio link has enough capacity to carry them. Other spy satellite operators such as France, China and India have to wait until their satellites appear over their ground stations before receiving the recorded images.

The atmosphere limits what spy satellites can see in several ways. Cloud cover prevented the early spy satellites from taking useful photographs much of the time. It would be the late 1980s before the first radar spy satellite was in orbit able to see through the clouds – more about this later (Chapter 8). Even when the sky is clear of clouds, the hours of darkness prevent detailed photographs being taken. Most of the Soviet Union is north of 50° latitude and much of it above 60°. The good news for American spy satellites was that the summer provided long hours of daylight, but the bad news was that winter nights were equally long. Paranoid American military analysts worried about what the Soviets might be up to during those long hours of darkness. By contrast, all of the continental USA is south of the 49th parallel, making the summer/winter contrast less extreme for Soviet spies in the sky.

Even when clear and in daytime, the atmosphere is turbulent. We see this for ourselves when viewing the stars – the twinkling of starlight is due to the shimmering of the atmosphere. This atmospheric turbulence puts limits on the accuracy of spy satellites. Although accuracy figures for the latest spy satellites are secret, we can work out the accuracy achievable with the Hubble Space Telescope if it were to point at the earth, which will give us a rough idea of what is possible. Hubble was designed to have a resolution of about 15–30 millionths of a degree.[5] If the atmosphere were

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[5] Chaisson (1998) p. 29.

completely still and Hubble was pointing at the earth from a typical spy satellite altitude of 250 km, it could resolve objects on the earth's surface of about 5–10 cm (2–4 inches) in size.

What do we mean by a resolution of 10 cm? It doesn't mean that two objects 10 cm apart will always be recognized as two objects and that two objects 8 cm apart will always be recognized as a single larger object. The ability to detect the small gap between two objects will depend on factors such as lighting conditions, the shapes and surfaces of the objects, shadowing in the gap, and the color and sheen contrast between the two objects and between them and the gap. It means that, in general, objects 10 cm apart will be recognized as being separate, while objects 8 cm apart will be more likely to be recognized as a single object. It also means that a gap of 1 cm, say, between two objects would hardly ever be detected.

Telescopes can focus an image onto a film down to a limit set by the color (wavelength) of the light. The resolution of the spy satellites comes down to how sharply you can focus light onto the film and the inherent graininess of the film itself. Early spy satellites generally worked at the limit of both of those parameters – the smallest image picked up by the telescope roughly equal to the graininess of the film.

Digital cameras and the camera in our cell or mobile phone have familiarized us with the term *pixel* or picture element. A camera that takes images containing 5 million pixels gives better pictures than one that contains 2 million pixels. If you blow up the picture, the graininess in the 2-million-pixel image becomes evident, whereas the 5-million-pixel image still looks sharp. When graininess appears, you have reached the ultimate resolution of the picture – objects smaller than the graininess are blurred and can't be resolved.

Even if a surveillance satellite has a resolution of, say, 10 m, it may be possible to detect and interpret features smaller than that. A satellite image with 10-m resolution of a 15-m-wide road may well show the white lines along the center of the road. The white line is only 5 cm wide so you could argue that the image has 5-cm resolution. This illustrates that the contrast in brightness between two objects (the 15-m-wide road and the 5-cm-wide white line) can make an object visible even though it is much smaller than the theoretical resolution of the image. The figure of 10-m resolution in this case is presumably based on some sort of average conditions.

An example of getting information that is better than the resolution in the military sphere is to work out the width of a missile to see whether it complies with a Treaty agreement. It should be possible to tell this with an accuracy as much as 10 times better than the image resolution, because the rim of the missile is made up of several pixels, giving us an averaging effect. I can speak for this personally through two commercial systems that I have been involved with in recent years.[6] In the first one for a Japanese customer, our software compares features in a satellite picture of the earth with features stored in a computerized digital map. The purpose is to work out from this comparison how much the image is distorted or the satellite is mis-

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[6] At my employer, Logica plc.

pointing. The resulting accuracy is 10 times better than the size of an individual pixel. The second system was for a European customer and achieved similar sub-pixel accuracy in monitoring the movement of clouds from one satellite image to the next – thereby measuring the speed and direction of the wind (more about this particular topic in the next chapter).

So, the quality of a spy satellite image is not a simple resolution value in meters or centimeters. A sophisticated scale of quality from 0 (worst) to 9 (best) was defined by the National Reconnaissance Office in terms of the information you could obtain from the image. For example, to say that an image was level 4 meant that you could see whether the door of a missile silo was open or closed and was equivalent to a resolution of about 2 m. At level 6 or about 50-cm resolution, you could distinguish between several different types of missile. We will return to this topic in Chapter 8, in which Figure 109 outlines the military view of image resolution.

During the Cold War, Robert Kohler, then at the CIA, recalls that in addition to defining what each quality level was in words, they tried to have an image that illustrated each level. It proved difficult to find an image, even a low-level airborne image, with level 9 quality – the highest possible quality level. Finally, a picture taken by an aircraft flying along the border between East and West Germany proved to have the required quality – it showed an East German soldier urinating. The image was displayed for all to see under the banner headline "German soldier pissing in the snow – level 9".[7]

The four pictures in Figures 1, 2, 3 and 4 are courtesy of John Pike and his GlobalSecurity organization.[8] They show two newspaper front pages, a vehicle license plate and a golf ball in images of various resolutions. Figure 1, with a resolution of 10 cm, is probably the best that spy satellites can do and doesn't come close to reading the headlines or the number plate nor even detect the golf ball – no chance to use these satellites to find that golf ball in the rough, then! Figure 2 shows the quality available from some aerial imaging systems and this probably can detect the golf ball but nothing else. Figure 3, with a resolution of 1 cm, allows you to read large tabloid headlines but not the license plate or normal headlines – but, interestingly, does resolve the picture on the *New York Times* front page quite well. Finally, Figure 4, with 1-mm resolution, which is way beyond the capability of current satellites, shows what the other images miss – the golf ball is distinguished as circular and not a small white box, the license plate is revealed and headlines, pictures and text in both newspapers are legible.

The Hubble Space Telescope was developed more than 20 years ago, so we might expect current spy satellites to be somewhat better in their performance. But the fact remains that resolving from space details on the surface of the earth that are smaller than a few centimeters is almost impossible. Forget about recognizing Osama Bin Laden as he walks down the street (even if he conveniently looks up to the sky at the

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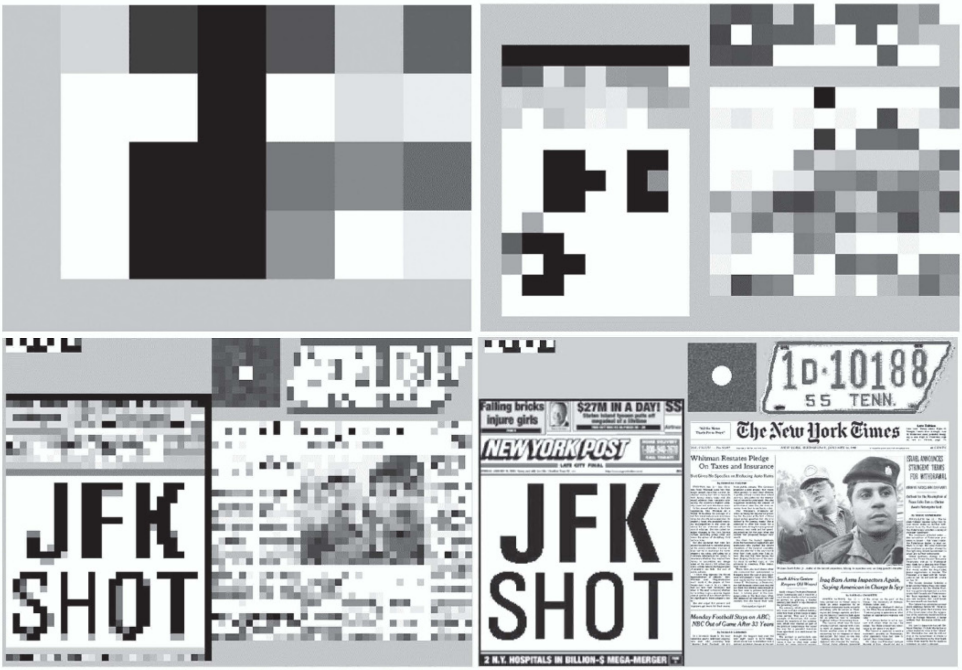
[7] McDonald (2002) p. 223.

[8] *www.globalsecurity.org.*



Figures 1, 2, 3 and 4. Simulation of images with various resolutions: 10 cm (Figure 1, high-quality spy-satellite image), 3 cm (Figure 2, high-quality aerial photo), 1 cm (Figure 3) and 1 mm (Figure 4). Courtesy John Pike and *GlobalSecurity.org*.

right moment!) or reading car license plates – or the newspaper headline. Photos that have been released show that it might occasionally be possible to identify the make and model of a car.

And all of that assumes that the atmosphere is absolutely still – which it hardly ever is. The atmosphere is constantly moving due to thermal gradients within it. On a really hot day, the shimmering is visible to the naked eye, for example, above a tarmac surface or a hot sandy beach. As you look further and further through the air, the thermal shimmering accumulates, so that through a telescope or strong binoculars, the shimmer is quite apparent. Even in the cool of the night, the shimmering air causes the stars to twinkle. In astronomical photos, the atmospheric shimmer is about 1 second of arc, which, in a photo of an object 100 km distant, is about 50 cm. Thus, because of this shimmer, an astronomical telescope photographing a satellite overhead could not make out features smaller than 50 cm – and more or less the same applies in the reverse direction with a spy satellite taking photos of the ground. The technology in a modern digital camera that removes jitter or focuses on eyes can get around this air shimmer to some extent. The software in a digital camera detects each jitter event by seeing objects in the picture move and moves the camera lens in the opposite direction. Satellite cameras have always done something like this – in the one-thousandth of a second (a millisecond) needed to take an image, the satellite has moved across the ground by about 8 m.

Satellite designers compensate by moving a mirror inside the camera in the opposite direction to avoid what would otherwise be a blurred image. Overcoming air shimmer takes this idea a bit further in that software in the satellite would find a suitable object in the picture – the edge of a building or a river or any sharp feature – and if it moves more or less than expected, adjust the mirror movement accordingly. Astronomers on earth are using this concept to take images as sharp as those of Hubble in space, so it seems likely that military imaging satellites are doing the same from space.

Legislators have tended to focus on resolution when formulating laws on satellite imaging. They have generally ignored other features of the satellites that can be just as important as resolution in allowing objects to be detected and analyzed. These other characteristics include the ability to distinguish color – or spectrum, to give it a technical name. Color in the images (as opposed to black and white) makes it possible to distinguish between crops, for example, and how healthy they are. It may also allow you to analyze the plume emitted by a rocket and thus tell what fuel it is using. The ability to analyze the brightness of an object is another important feature. An image that distinguishes subtle shades of gray will tell us much more than a simple black-and-white picture. The resolution of an image can be improved by taking two or more photos of the scene from slightly different angles. Combining the images will provide an image that has better resolution than one image on its own – provided the scene hasn't changed in the meantime. A single satellite with a simple camera may take an image of the same scene for several days; thus, if a satellite or group of satellites has the ability to take a repeat image within a short time (seconds or minutes or even hours), that is important. A variation on this revisit feature is to combine two images to give a stereo view of the scene – features not evident in either image can stand out, literally as well as metaphorically, in the stereo image. These other capabilities are not covered in current legislation of surveillance by satellite, thereby weakening what legislation there is on the subject.[9]

THE MAKINGS OF A SATELLITE

Let's take a look at a typical imaging satellite.

The artist's impression of the 4-ton JAXA (Japan's space agency) Daichi satellite launched in January 2006 (and previously called ALOS) in Figure 5 shows many features typical of all earth-observing satellites. The satellite is dominated by the elongated solar array panel on the right. The sun-facing side of this panel is covered with solar cells that convert sunlight into electricity. Daichi's solar array is 22.2 m (73 ft) long and 3.1 m (10 ft) high. It is made up of nine panels that are folded concertina-fashion for the launch (on the left in Figure 6) then unfold once the satellite is in orbit. You may have seen pictures of the International Space Station,

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[9] Hanley (2000).

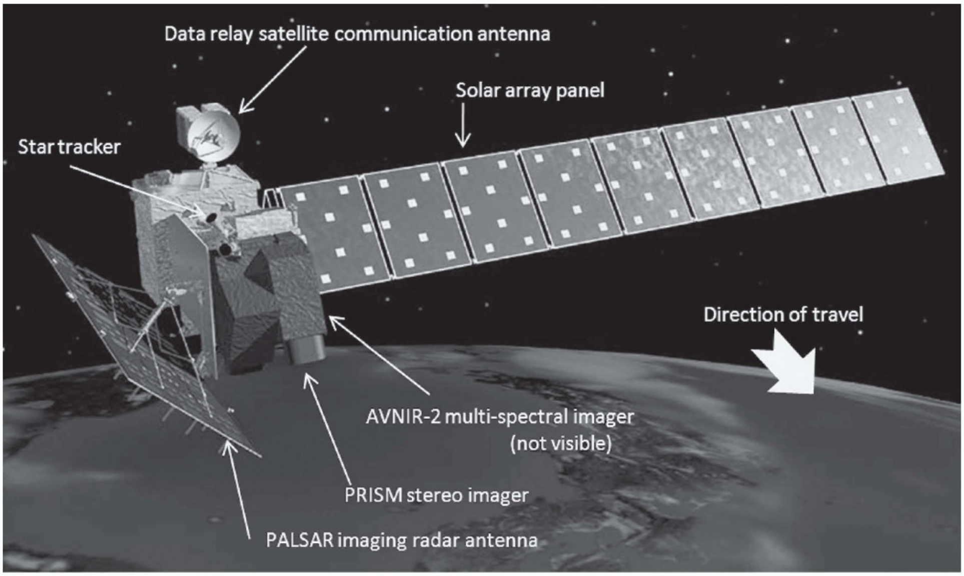

Figure 5. Artist's impression of Japan's Daichi satellite showing the main features of a surveillance satellite. Courtesy JAXA.

which is also dominated by its several solar arrays, indicating the importance to all satellites of a sustainable source of electrical power – this allows them to stay in orbit for many years.

On the left of the artist's impression (Figure 5) is another panel, which is the antenna for the imaging radar – the radar is sufficiently complex and sophisticated to be given a name of its own: PALSAR.[10] It is almost 9 m (29 ft) long and 3.1 m (10 ft) high. Although the eventual information from PALSAR is images, it is not a camera or telescope. It forms images by measuring the individual echoes of its radar transmission from each point on the ground below. Each individual echo is then considered as a pixel to form an image. The transmission and returning echo are radio signals, hence the need for an antenna.

Daichi carries two other imaging instruments. The PRISM[11] instrument is a triple camera that can take stereo images using three telescopes that point towards the ground at slightly different angles – you can just make out two of the three telescopes in the image. One points straight down and the others point forward and backward. The three images are combined on the ground to create stereo imagery, which is helpful for analyzing ground contours. The resolution of the images is 2½ m directly below the satellite but tails off as you look to either side.

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[10] PALSAR is an acronym of Phased Array type L-band Synthetic Aperture Radar.
[11] PRISM = Panchromatic Remote-sensing Instrument for Stereo Mapping.

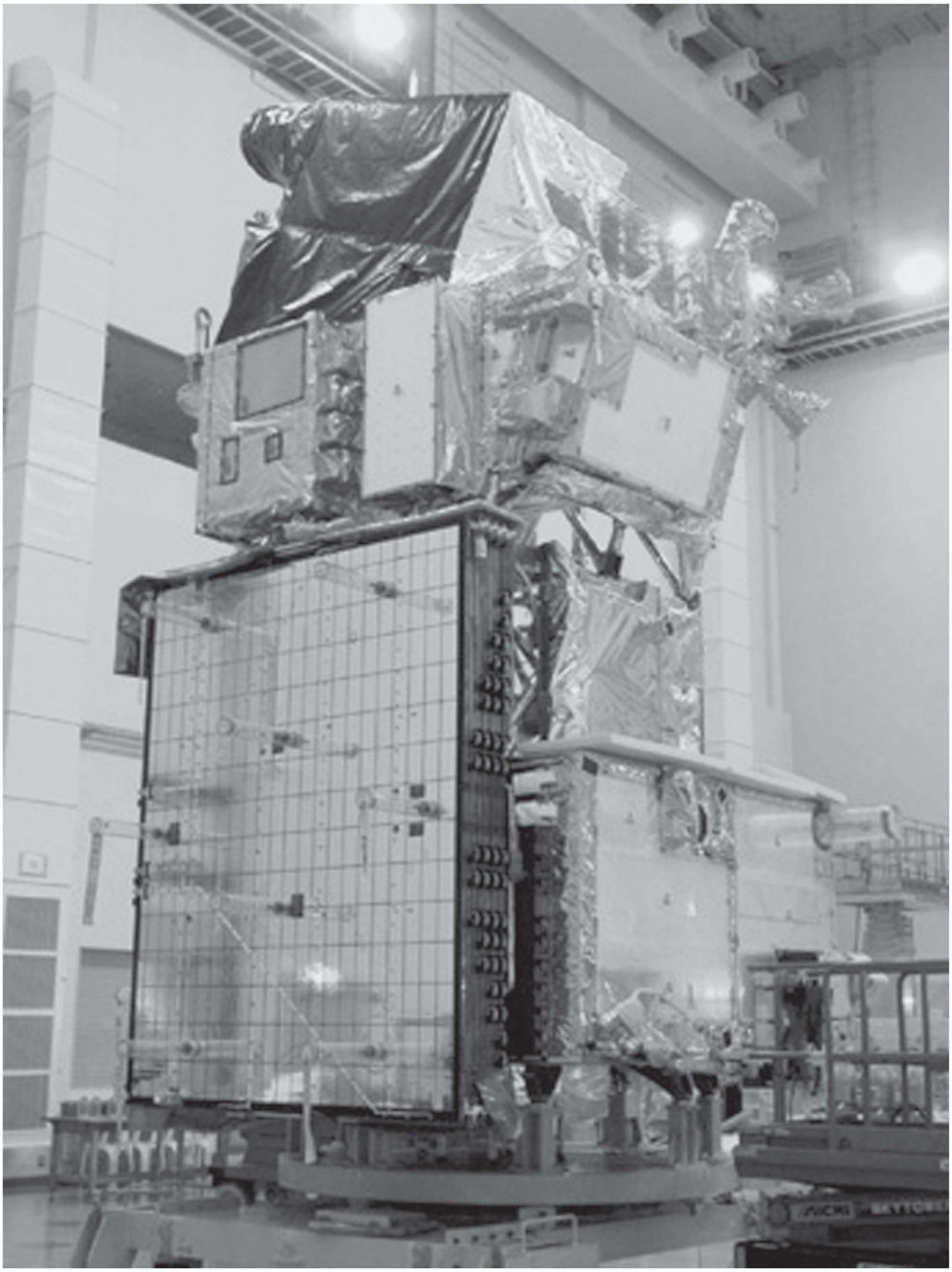

Figure 6. Daichi before being launched. Courtesy JAXA.

The final imager is called AVNIR-2,[12] which takes images in four colors, one of which is in the infrared and detects heat – this means that it can take images at night, with cold objects appearing black and warm ones bright. To take the color images, AVNIR-2 is effectively made up of four separate cameras, one for each color – the cameras all stare through the same telescope thanks to a clever arrangement of mirrors that focuses the scene onto all four cameras simultaneously. The images have a resolution of 10 m.

The main body of the satellite in Figure 5 is roughly a rectangular box, 6.2 × 4 × 3.5 m. It is packed full of fuel tanks, electronics, batteries and the like. The fuel feeds its small rocket motors that keep it pointing in the right direction and make small changes to its orbit from time to time. The batteries are charged up when the satellite is in sunlight and are used to power the equipment on the satellite during the periods (sometimes a third of the orbit) when the sun is hidden behind the earth. The star tracker shown on the top of the main body ensures that the satellite is pointing in the right direction – it takes images of the dark sky overhead (the sky is always black in outer space) and identifies the brightest stars in its field of view so that it knows which way is up.

Above the main body is a small dish antenna that communicates with a satellite in geostationary orbit (36,000 km above the earth). By having this dish, Daichi is able to immediately send its images to the ground when it is in view of the relay satellite. Without it, Daichi would have to store the images in its onboard memory and wait until a suitably equipped ground facility was in view. The geostationary satellite normally used by Daichi is Japan's Data Relay Test Satellite (DRTS, also called Kodoma), which is specially equipped to receive the transmission from satellites like Daichi. Kodoma is an experimental satellite and a replacement is not currently funded. Located over the Indian Ocean, it can pick up data when Daichi is over Asia, the Indian Ocean and the eastern Pacific Ocean. To deal with imagery of other parts of the globe or if Kodoma is not available, Daichi also has the ability to work in the conventional way – storing onboard and transmitting when a station is close.

In 2010, Daichi started sending images to earth through NASA's TDRSS relay satellites (see below), thus doubling the number of images of the western hemisphere that it can provide.[13] Europe's ARTEMIS[14] is similar to Kodoma and is used by other surveillance satellites such as France's SPOT satellites.

Not many satellites have the ability to communicate with a geostationary satellite like this. In the past, the USA and Russia were the only countries with the technology to do it. The USA has a fleet of eight Tracking and Data Relay Satellite System (TDRSS) geostationary satellites for this purpose: TDRSS-C through -J (TDRSS-A was switched off in June 2010 after 27 years in use; TDRSS-B was destroyed in the explosion of the Space Shuttle Challenger in 1986) (see Figure 7).

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[12] AVNIR-2 = Advanced Visible and Near Infrared Radiometer type 2. AVNIR-1 was onboard the ADEOS satellite launched in 1996.

[13] Morring (2010a).

[14] ARTEMIS = Advanced Relay and TEchnology MISsion.

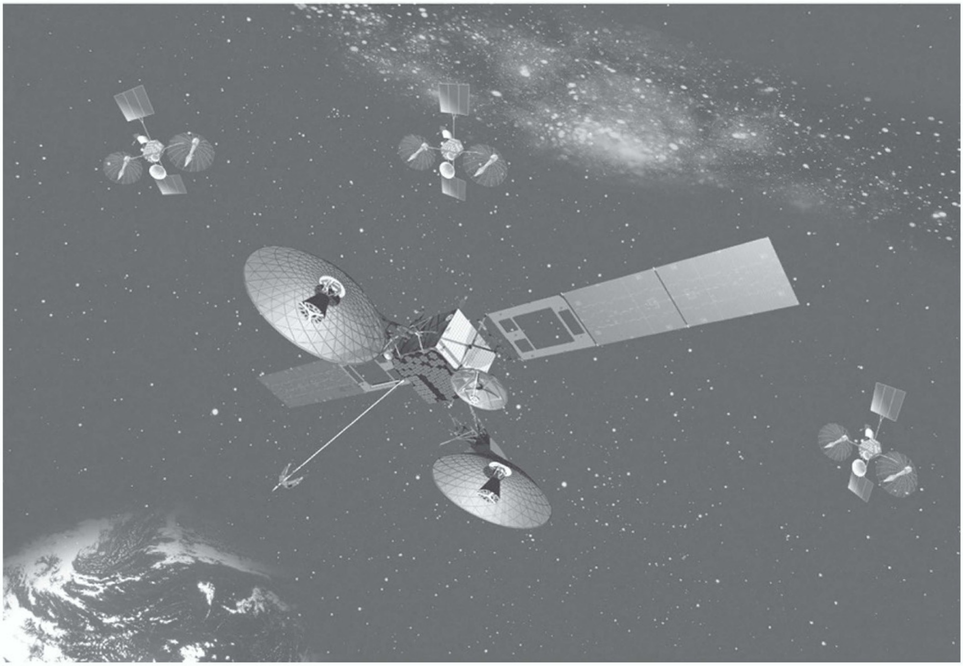

Figure 7. Artist's impression of four of NASA's TDRSS satellites in orbit. Each of its big dishes can communicate with a separate satellite in orbit far below. Credit: NASA.

The TDRSS satellites act as relays for transmissions from NASA vehicles and satellites such as the Space Shuttle, the International Space Station, the Hubble Space Telescope and various earth-observing and scientific satellites. The two big dishes on TDRSS are 4.9 m (16 ft) wide and each can lock on to a separate satellite – Japan's Kodoma and Europe's ARTEMIS can only cope with one satellite at a time.

The advantage of the TDRSS group of satellites is that they see a satellite in a low orbit for more than 85% of that orbit whereas each ground station would see the low-orbiting satellite for only about 10% of the orbit – so TDRSS is as good as eight or nine stations and avoids the need to find willing countries suitably located to give continuous coverage of the orbiting satellites. The disadvantage of TDRSS is that each TDRSS is pretty expensive and each satellite that uses it has to carry an antenna that can lock on to TDRSS and steer itself to stay locked on as it moves in its orbit. Furthermore, TDRSS itself needs a ground station, and a particularly complex one at that, since it is effectively dealing with dozens of different satellites around the world. The complexity of the station was brought home to NASA when an upgrade in the 1990s cost a lot more and took a lot more time than was intended.

Unlike NASA, the commercial world has tended to prefer the ground station option rather than the geostationary relay option. Commercial satellites can usually afford to wait a few hours to get their images back, whereas NASA wants instant and continuous links to the Space Shuttle and the International Space Station. Commercial satellites therefore benefit from the recent advances in mass storage –

consider the number of images you can now store on a tiny chip in your digital camera compared with just a few years ago. The satellites store the images until they are in sight of the station. The commercial operators also benefit from the trend to leave ground stations virtually unmanned – with maintenance staff visiting perhaps once a week and security provided by basing the station in a larger complex, such as a commercial park or a military base.

Mind you, NASA's Landsat satellites have been thankful that they were equipped to send their images back through TDRSS. The two radio transmitters on Landsat 4 for sending images direct to ground both failed, leaving TDRSS as the only way to get its images back.

The US military has its own relay satellites called SDS-2 and QUASAR[15] in high orbits, not all geostationary, allowing them to relay images from surveillance satellites over the poles, which would be out of view of a geostationary satellite. Some US military satellites also use TDRSS. Russia has similar relay satellites for its military surveillance satellites. This topic is discussed further in Chapter 8. Although most of the remainder if this book is about why satellites are watching the earth, I will return to how satellites work from time to time when a specific feature not described above is being discussed. You can find these sections in the index at the end of the book under "How satellites work".

Let's now turn to the topics mentioned at the start of the book, beginning with the terrorist attack in Mumbai.

MUMBAI ATTACKS, NOVEMBER 2008

The 10 Pakistanis who came ashore on the evening of November 26th 2008 may never have been to Mumbai, India, before, but their trip had been prepared by others who had. One hundred and seventy-five people died in the 3 days of terror, including all but one of the terrorists. The terrorists took cabs from where they came ashore to the five target locations, thereby not requiring any great geographical knowledge. A detailed dossier of their movements and planning was compiled by the Indian Government based on information from the one captured terrorist and physical evidence such as the logs in the four GPS satellite navigation devices recovered (one on their boat), intercepted phone calls, and phones and documents found on the terrorists and in their boat.[16] The dossier was given to the Pakistani Government to persuade them to arrest several Pakistani residents identified by India as being implicated in the plot.

The group left Karachi in Pakistan on November 22nd 2008, 550 km from their destination, and hove to 7 km off the coast of Mumbai about 4 p.m. on Wednesday November 26th. They waited until darkness, killed the captain of the boat (which

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[15] SDS-2 = Space Data Systems second generation.

[16] Indian Government (2009).